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JASA ARTICLE

Predicting the exposure of diving grey seals to shipping noise[a]

Leah E. Trigg,[1,b] Feng Chen,[1] Georgy I. Shapiro,[1] Simon N. Ingram,[1] Cécile Vincent,[2] David Thompson,[3] Debbie J. F. Russell,[3,c] Matt I. D. Carter,[3,d] and Clare B. Embling[1]
[1]*School of Biological and Marine Sciences, University of Plymouth, Plymouth PL4 8AA, United Kingdom*
[2]*Centre d'Etudes Biologiques de Chizé, CNRS/University of La Rochelle, La Rochelle, France*
[3]*Sea Mammal Research Unit, University of St Andrews, St Andrews, Fife KY16 8LB, United Kingdom*

ABSTRACT:
There is high spatial overlap between grey seals and shipping traffic, and the functional hearing range of grey seals indicates sensitivity to underwater noise emitted by ships. However, there is still very little data regarding the exposure of grey seals to shipping noise, constraining effective policy decisions. Particularly, there are few predictions that consider the at-sea movement of seals. Consequently, this study aimed to predict the exposure of adult grey seals and pups to shipping noise along a three-dimensional movement track, and assess the influence of shipping characteristics on sound exposure levels. Using ship location data, a ship source model, and the acoustic propagation model, RAMSurf, this study estimated weighted 24-h sound exposure levels (10–1000 Hz) (SEL_w). Median predicted 24-h SEL_w was 128 and 142 dB re 1 μPa^{2}s for the pups and adults, respectively. The predicted exposure of seals to shipping noise did not exceed best evidence thresholds for temporary threshold shift. Exposure was mediated by the number of ships, ship source level, the distance between seals and ships, and the at-sea behaviour of the seals. The results can inform regulatory planning related to anthropogenic pressures on seal populations.
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I. INTRODUCTION

Global commercial shipping underpins trade and economic development, and with the globalisation of manufacturing and financial markets, shipping has increased dramatically since the start of the 20th century (Hoffmann and Kumar, 2010). The carrying capacity of the world commercial fleet has increased by 1.6×10^9 deadweight tonnes since 1970 and was carried by more than 94 000 ships in 2018 (UNCTAD, 2018). Commercial ships emit low frequency underwater noise from propeller cavitation, machinery onboard the ship, and the flow of water past the vessel (Urick, 1983). This has been linked to a 3.3 dB per decade increase in underwater ambient sound levels between 1950 and 2007 (Frisk, 2012). An increasing weight of evidence suggests that shipping noise, defined as water-borne sound (ISO, 2017) from motorised watercraft (Erbe *et al.*, 2019), can have a detrimental effect on marine mammals through mechanisms such as communication masking (Hatch *et al.*, 2012; Jensen *et al.*, 2009), behavioural change (Blair *et al.*, 2016; Dyndo *et al.*, 2015; Mikkelsen *et al.*, 2019), and physiological changes such as hearing damage (Finneran, 2015; Jones *et al.*, 2017; Rolland *et al.*, 2012).

As central-place foragers that return to haul-out sites to rest, breed, and moult, seals heavily utilise the coastal zones that are also home to busy shipping lanes. Jones *et al.* (2017) highlighted a high rate of daily co-occurrence for harbour seals, grey seals, and shipping within 50 km of the coast. Evidence suggests that seals can flush into the water when cruise ships pass haul-out sites (Jansen *et al.*, 2015), and exhibit alert and orienting behaviour in response to the sound of boat playbacks (Tripovich *et al.*, 2012). In addition, Mikkelsen *et al.* (2019) report 2.2%–20.5% of the at-sea time of tagged grey and harbour seals in the North Sea contained audible shipping noise.

However, there is still very little information about the at-sea exposure of seals to shipping noise and their spatial relationship with shipping given their three-dimensional use of the underwater environment. Grey seals (*Halichoerus grypus*) frequently dive ~200 m to the seafloor of the continental shelf, although where habitat permits, they can exceed this depth (Jessopp *et al.*, 2013; McConnell *et al.*, 1999; SCOS, 2018; Photopoulou *et al.*, 2014; Thompson *et al.*, 1991). Evidence suggests that they can potentially experience differential noise exposure of up to 10 dB as they undertake such movement vertically throughout the water column (Chen *et al.*, 2017). To assess noise from shipping, predictions primarily take the form of two-dimensional maps (Erbe *et al.*, 2014). However, these maps often neglect or average the influence of depth. This may be particularly problematic when assessing the exposure of seals in shallow shelf seas, which are regions of intersection

[a]This paper is part of a special issue on The Effects of Noise on Aquatic Life.
[b]Electronic mail: leah.trigg@plymouth.ac.uk, ORCID: 0000-0003-3764-7003.
[c]ORCID: 0000-0002-1969-102X.
[d]ORCID: 0000-0002-5481-6254.

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between dynamic environmental properties that influence sound propagation and high density shipping (Simpson and Sharples, 2012).

Phocid seals have a functional hearing range from 50 Hz to 80 kHz (National Marine Fisheries Service, 2018), which overlaps with the dominant frequencies of noise from large commercial ships (10–1000 Hz). Seals utilise sound production and reception during mating, mother-offspring interactions, and while maintaining territory (Hayes *et al.*, 2004; Van Parijs *et al.*, 2001). Grey seals vocalise at frequencies between 100 and 500 Hz (Asselin *et al.*, 1993) placing them at risk of communication masking by shipping noise (Bagočius, 2014). Exposure to underwater noise from shipping has the potential to induce temporary or permanent threshold shift, exhibited by an increase in the threshold level at which an animal can hear at a given frequency (Southall *et al.*, 2007; Southall *et al.*, 2019). The mean daily sound exposure level measured at the Port of Vancouver's inbound shipping lane and weighted using a frequency weighting function for underwater phocid pinnipeds was 156 [standard deviation (SD) = 1.3] dB re 1 $\mu Pa^2 s$ (Martin *et al.*, 2019), which did not exceed the 181 dB re 1 $\mu Pa^2 s$ threshold for the onset of temporary threshold shift (TTS) from non-impulsive underwater noise (ISO, 2017; Southall *et al.*, 2019). However, these measurements did not consider seal habitat use. Jones *et al.* (2017) modelled the exposure of harbour seals in the Moray Firth, Scotland, UK, to shipping noise using seal tag movement data and reported that when considering upper confidence intervals some estimates did exceed the threshold for the onset of TTS. These predictions were only based on the two-dimensional location of seals at-sea and suggest there is still great uncertainty associated with sound exposure predictions.

In response to evidence of the negative impact of underwater noise on marine mammals, a number of international regulatory bodies are taking steps to mitigate the risks associated with shipping noise (European Commission, 2008, 2010, 2017). However, effective management is still constrained by a lack of data pertaining to the exposure of marine life to shipping noise. As a result, it is difficult for policy to set targets for acceptable noise levels without data on historical and current noise levels against which to track trends and measure the effectiveness of policy to mitigate noise (Merchant *et al.*, 2016). It is necessary to understand the exposure of an individual, and consequently populations, in order to explore the impact of this exposure on marine animals (Merchant, 2019; Van der Graaf *et al.*, 2012).

Consequently, this study aims to predict the exposure of individual seals to shipping noise using a sophisticated underwater acoustic propagation model and the three-dimensional location and dive tracks of tagged grey seals. Specifically, the study aims to investigate the at-sea exposure of grey seals at two different life stages: pups and adults. The seal tracking data will link noise exposure directly to at-sea vertical and horizontal spatial use by seals, improving the applicability of the results to risk calculations and marine spatial planning. The study also aims to investigate the influence of ship source level, the number of ships, and the proximity of ships to seals on predicted noise exposure levels.

II. METHODOLOGY

This study undertook a historical reconstruction of 24-h weighted sound exposure levels (SEL_w) (ISO, 2017) for seal pups in the Celtic Sea and adult seals primarily located in the English Channel with respect to shipping noise (Fig. 1). These regions host high volume shipping lanes (Fig. 2) but grey seals also utilise breeding and haul-out sites along the coast, resulting in significant overlap between grey seals and shipping (Jones *et al.*, 2017; SCOS, 2018). The region is a good example of a dynamically active, shallow, shelf sea characterised by mesoscale eddies and fronts, as well as the development of a strong thermocline in the summer (Pingree, 1980), and the influence these properties have on sound propagation (Shapiro *et al.*, 2014). Seals were tagged with Fastloc® Global Positioning System/Global System for Mobile Communication (GPS/GSM) tags (SMRU Instrumentation), which provided location and dive data for each seal. The seals were tagged as part of separate studies on animal movement and habitat use from 2009 to 2013 (Huon *et al.*, 2015; Thompson, 2012). Weighted sound pressure levels (SPLs) (ISO, 2017) from ships in a 24 h period were predicted along each seal's three-dimensional track using historic records of ship movements, a ship source level model and a range dependent acoustic propagation model.

A. Seal location and movement data

The details of 18 seals included in the study are given in Table I. Celtic Sea animals were tagged in 2009 or 2010 at sites on Anglesey or Ramsey Island, Wales, UK (Table I, Fig. 1) under Home Office Licence No. 60/4009. English Channel animals were tagged in the Iroise Marine Park under licence Nos. 10/102/DEROG and 13/422/DEROG provided by the French Ministry of the Environment (Fig. 1). Seals were caught, anaesthetised using Zoletil® (Vibrac, France) where necessary, and tags were glued to clean, dry fur at the base of the neck using epoxy resin or cyano-acrylate contact adhesive. The tagging methodology followed McConnell *et al.* (1999) and is explained in detail by Thompson (2012, p. 6), Huon *et al.* (2015, p. 1093), and Carter *et al.* (2017).

Erroneous GPS locations were identified as those obtained using fewer than five satellites and/or having high residual error values from the Fastloc® position algorithm (Dujon *et al.*, 2014; Russell and McConnell, 2014). These were removed, and tests on land reveal that such procedures can result in a distance error <50 m for 95% of locations (Russell and McConnell, 2014). An animal was given the status "diving" when the tag registered a depth of 1.5 m or deeper for greater than 8 s. A dive ended when depth was shallower than 1.5 m. In order to produce a three-dimensional track for each seal, the timestamps of location and depth points transmitted by the tags were used to interpolate each dive in space using hermite curve interpolation

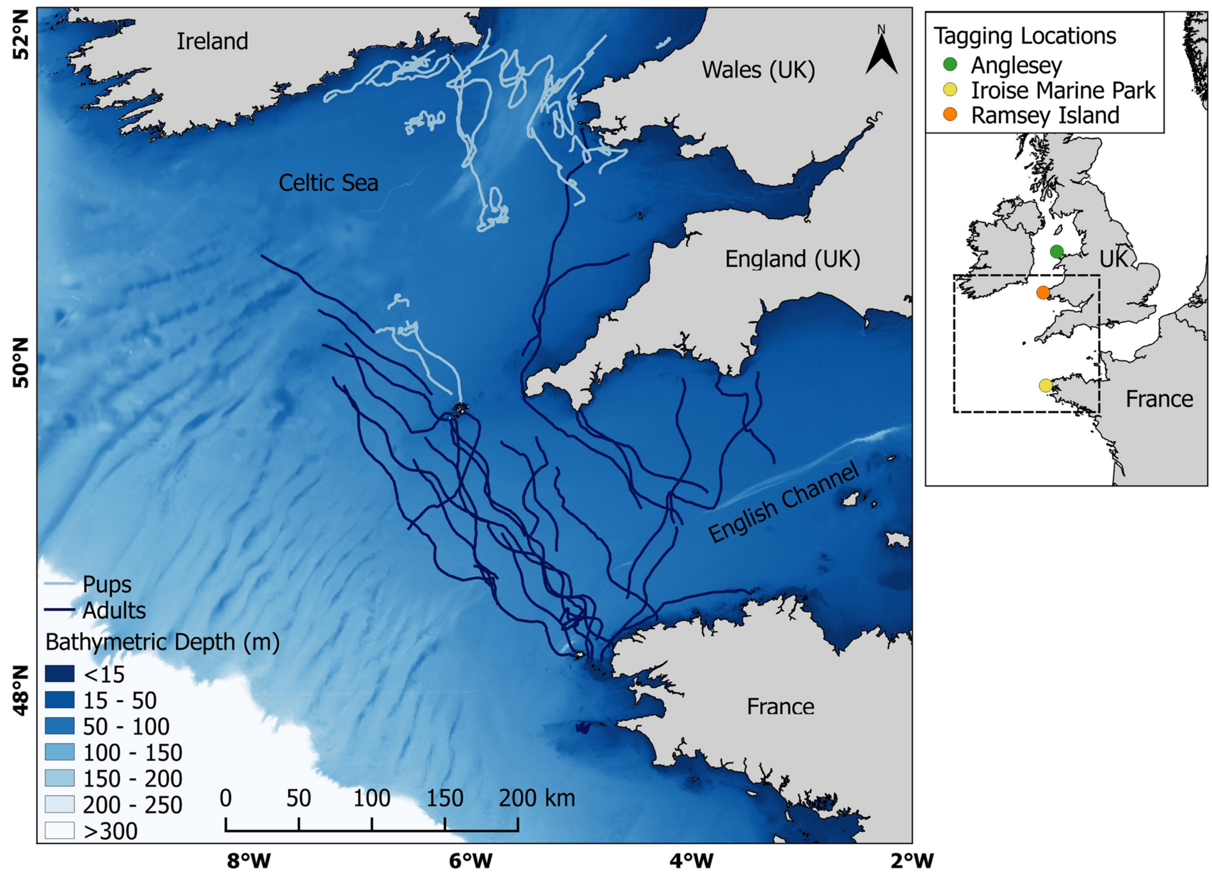

FIG. 1. (Color online) Map of study area showing the bathymetric depth of region and 24 h seal track segments used to calculate weighted sound exposure levels. Navy blue tracks are adult seals tagged in the Iroise Marine Park (Inset map: yellow dot). Light blue tracks are seal pups tagged on Anglesey (Inset map: green dot) or Ramsey Island (Inset map: orange dot), Wales, UK.

(Kuhn *et al.*, 2010; Tremblay *et al.*, 2006). The tags attempt to record regular location fixes but they rely on the seal surfacing to capture satellite data (Carter *et al.*, 2016). As a result, the time between location points can vary, and there can be bias in the number of GPS points to locations where the seal is not diving. To address this, the interpolation also re-sampled the seal track at a rate of 1 s to produce a track with regularly spaced location points. Hermite curve interpolation can more closely represent the curvilinear paths of animals moving through a fluid environment than linear interpolation (Tremblay *et al.*, 2006). Dives that were not within 180 min of a GPS fix were excluded to reduce error in interpolated locations (Carter *et al.*, 2017). This value retains as much continuous track as possible while limiting error.

In order to calculate at-sea 24-h sound exposure levels, periods of haul-out were excluded and track segments that were 24 h in duration were extracted. Haul-outs were determined by the wet/dry sensors aboard the tag and periods of haul-out were transmitted as part of the tag data message. In addition, track segments had to be located entirely within the study area to ensure Automatic Identification System (AIS) data coverage and overlap in time and space with environmental datasets for acoustic modelling. The 24-h track segments along which noise was estimated are shown in Fig. 1 and the number of days processed for each seal is shown in Table I. The mean maximum dive depth and mean inter-dive interval for all seals was 34.7 (SD = 32.8) m and 58.1 (SD = 51.4) seconds, respectively.

B. Ship location data

This study utilised historical data from terrestrial AIS to determine the location of ships at sea in relation to the grey seal tracks. AIS data were obtained from ShipAIS (ShipAIS, 2018) and Marine Traffic for time periods that overlap with the seal data. Each dataset provided coverage for a subsection of the total study area (Fig. 1), but overall this resulted in complete coverage of the area (Figs. 1 and 2). The data from all sources were combined in a SQLite database and matched on the unique field "MMSI number."

A subset of 930 MMSI numbers were removed from the analysis because no data on vessel length was available; length was recorded as zero or they were identified as base stations and aircraft, resulting in 22 443 ships in the final AIS database. The data were split into transects. A transect was defined as containing more than one AIS location point, and the ship was moving at a speed over ground over 1.5 knots. Ships slower than this were likely to be stationary or drifting at anchor (Marine Management Organisation, 2014, 2015). A transect ended and a new transect started when

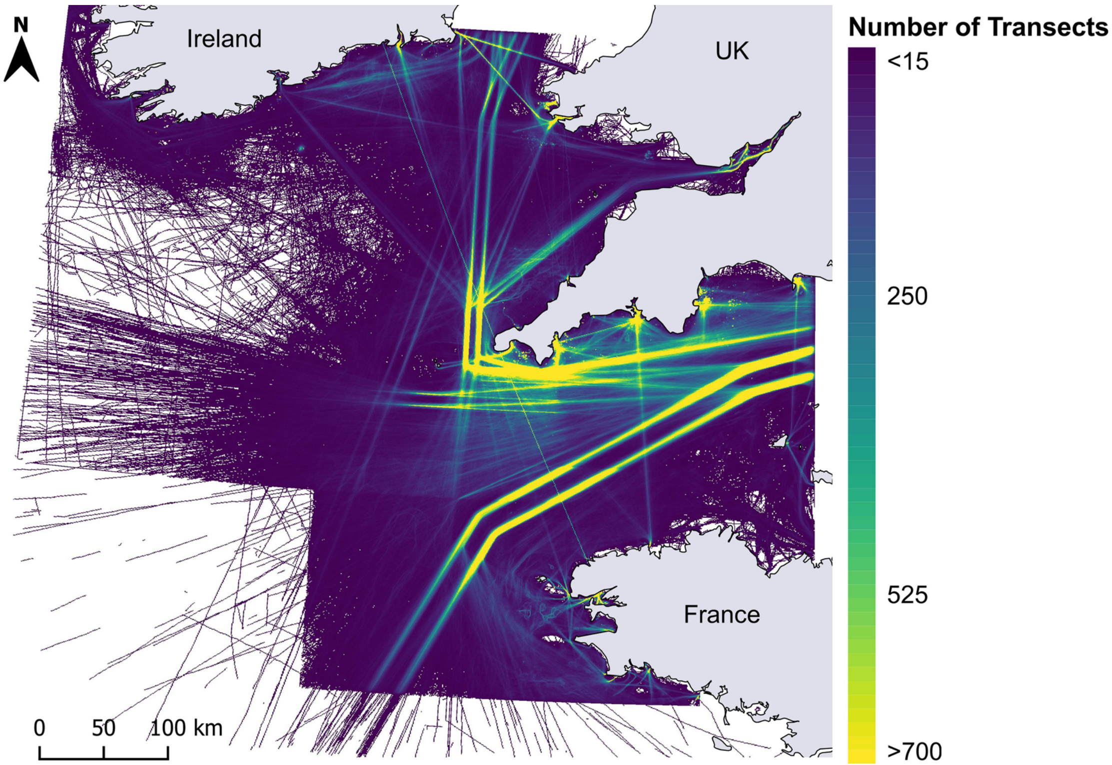

FIG. 2. (Color online) Ship transects derived from raw AIS data from all data sources. Shows AIS data coverage of area occupied by the seal tracks. Colour ramp shows total number of transects that intersect a cell for all data (approximately 1 km × 1 km). Data between 2% and 98% of range visualised. Transects are passages of a ship with more than 1 AIS location point, travelling at a speed over ground between 1.5 and 60 knots and with less than 180 min between points. Maximum number of transects passing through a cell was 352 690.

there was greater than 180 min between location points. The next point was the start of a new transect. This 180 min time interval was short enough to resolve ships rounding Land's End, UK, and heading north into the Celtic Sea, as well as those leaving and returning to the study area, while retaining the presence of as many ships as possible. The location of a ship along the transect at a particular time was estimated using linear interpolation.

TABLE I. Details of seal tag data used in the study. A total of 18 seals were included; nine adults and nine pups. Noise was calculated for a total of 86 days. The table shows the percentage of the total time the seal spent at sea used in the study. ISMP, Iroise Sea Marine Park.

ID	Location tagged	Mass (kg)	Sex	% track used	Days	Age Class
B23	ISMP	129	M	3.4	4	Adult
B24	ISMP	124	M	4.8	6	Adult
B26	ISMP	68	F	0.6	1	Adult
B27	ISMP	152	M	2.4	4	Adult
B31	ISMP	206	M	4.0	4	Adult
B32	ISMP	114	F	3.4	4	Adult
B33	ISMP	210	M	7.3	11	Adult
B35	ISMP	148	M	3.5	4	Adult
B37	ISMP	70	M	3.8	4	Adult
hg27-01-09	Anglesey	37	M	2.1	3	Pup
hg27-04-09	Anglesey	38	M	3.3	5	Pup
hg29-11-10	Anglesey	35	M	2.0	5	Pup
hg29-15-10	Ramsey	39	F	0.5	1	Pup
hg29-16-10	Anglesey	40	F	4.4	5	Pup
hg29-18-10	Ramsey	32	M	10.6	9	Pup
hg29-21-10	Ramsey	37	M	5.5	7	Pup
hg29-23-10	Ramsey	29	M	5.3	1	Pup
hg29-24-10	Ramsey	32	F	25.8	8	Pup

C. Ship source model

The source level (ISO, 2017) of each ship was calculated using the Research Ambient Noise Directionality (RANDI) model (Breeding *et al.*, 1996; Chen *et al.*, 2017; Erbe *et al.*, 2014; Jones *et al.*, 2017; Ross, 1976; Williams *et al.*, 2014). The model is based on the relationship between ship source level, speed, and vessel length and has a satisfactory agreement with monopole source levels (ISO, 2019) derived from measured data. RANDI has exhibited underestimates of 5–13 dB at frequencies greater than 200 Hz (Simard *et al.*, 2016), and median estimation errors of 0 (±7.1 dB) (Peng *et al.*, 2018) when compared to monopole source levels. There are several ship source level models available (Brooker *et al.*, 2015; Wittekind, 2014) and each of these models exhibit some level of disagreement (Jansen and de Jong, 2017; Karasalo *et al.*, 2017; Simard *et al.*, 2016) when compared to monopole source levels derived from measured data (Chion *et al.*, 2019; ISO, 2017). Given this variation between models, a deterministic one-way sensitivity analysis was conducted to assess the influence of source level and other modelling parameters on the predicted exposure of seals. The resulting uncertainty in predicted exposure was calculated by generating bootstrapped samples of SEL_w every 15 min along the seal track. A more detailed explanation of this analysis is included in the Supplemental Material.[1]

The length and speed of the ship for input into the RANDI model was derived from the AIS data. Spectral source levels were estimated at every 1 Hz between 10 and 1000 Hz and integrated to give 1/3 octave band source levels (ISO, 2017). The 1/3 octave band source level was obtained for each ship individually in a 15 min period using the ship's length and speed over ground at that point along its transect. Median broadband source levels in the database ranged from 132 dB re 1 μPa^{2}m^2 for ships <30 ft to 196 dB re 1 μPa^{2}m^2 for ships >630 ft. Ship source levels were not grouped into classes.

D. Acoustic propagation model

The parabolic equation model RAMSurf (Collins, 1993) was used to calculate propagation loss (ISO, 2017) between each sound source and the location of each seal. This model is suitable for range dependent, low frequency, shallow water scenarios (Etter, 2013). The horizontal and vertical step parameters for the acoustic model were fixed at 50 and 0.5 m, respectively, for all simulations. These ensured a convergent solution across all frequencies tested. Ships greater than 164 ft ($\sim$50 m) were assigned a source depth of 6 m (Scrimger and Heitmeyer, 1991) and smaller vessels a depth of 3 m (Erbe *et al.*, 2012b). The model considers detailed three-dimensional environmental changes. The environmental conditions were described along each transect by submitting the bathymetric depth, a sound speed profile for the water column, and geoacoustic parameters every 2 km to the maximum range of each transect. Sediment type was determined from the EMODnet Geology project seabed substrate map (1:1 000 000) (European Commission, 2016). Geoacoustic parameters for the model were extracted from the literature based on the percentage of mud, sand, and gravel given in the sediment classification (Hamilton, 1980; Long, 2006). The sound speed profile was calculated using the nine-term equation proposed by Mackenzie (1981). Temperature and salinity values for each profile were extracted from the Iberian Biscay Irish Ocean Reanalysis system (0.083 × 0.083 degrees resolution; 50 depth levels) available through the E.U. Copernicus Marine Environment Monitoring Service (CMEMS; product identifier: IBI_REANALYSIS_PHYS_005_002). Complete tables of model and geoacoustic parameters are given in the Supplemental Material.[1]

The bathymetry of UK and Irish waters was determined using the EMODnet Digital Bathymetry (DTM 2016) at 1/8 * 1/8 arc min resolution (EMODnet Bathymetry Consortium, 2016). This data is given in metres with reference to lowest astronomical tide but converted to mean sea level using the Vertical Offshore Reference Frame data generated by the UK Hydrographic Office (Adams *et al.*, 2006; Turner *et al.*, 2010). Bathymetric data for French waters were taken from the MNT Bathymétrique de facade Atlantique (Projet Homonim), which is provided in metres with reference to mean sea level (Shom, 2015).

Seal tag data provides depth with reference to the water surface. This varies in height with respect to the sea floor throughout the tidal cycle. The seals are diving throughout the tidal cycle and, therefore, can dive deeper than the bathymetry layer at certain points. This was minimised by using bathymetry with reference to mean sea level and noise exposure values were corrected to the noise level 5 m above the sea floor if there was a mismatch between maximum dive depth and bathymetric depth. The impact of this correction was assessed within the sensitivity analysis presented in the Supplemental Material.[1]

Simulations were conducted at the centre frequencies of one-third octave bands between 10 and 1000 Hz. This frequency range encompasses the maximum energy output for ships and covers both of the frequencies (63 and 125 Hz) recommended by the Marine Strategy Framework Directive as important for monitoring shipping noise (European Commission, 2008, 2010, 2017). However, it is noted that ship source levels do extend beyond this (Veirs *et al.*, 2015). The propagation loss output was smoothed to remove variation associated with the coherent nature of the model. This was completed using a moving average (Harrison and Harrison, 1995).

E. Construction of three-dimensional received noise levels

At each 15 min time step, a three-dimensional noise field of broadband (10–1000 Hz) weighted SPL (SPL_w) (ISO, 2017) was generated for the area enclosing the dive and location track of the seal (Fig. 3). SPLs (ISO, 2017) for each ship were calculated by subtracting smoothed propagation loss values, calculated using the RAMSurf model, from the ship source levels, calculated using the RANDI ship source model. The RAMSurf model output is two-dimensional (range and depth). Three-dimensional coverage of the area enclosing the seal track was generated by calculating propagation loss along multiple transects at an azimuth of 2.5°. This produced a noise field composing depth and range at multiple azimuths (Fig. 3). SPLs were weighted using two methods: the underwater m-weighting function proposed by Southall *et al.* (2007) for pinnipeds and the underwater frequency weighting function for phocid pinnipeds proposed by Southall *et al.* (2019). Broadband SPL_w (10–1000 Hz) was calculated by integrating across all frequencies (approximated by summation). Total SPL_w (10–1000 Hz) from all ships at each point along the seal track was calculated by summing the noise intensity of each ship as shown in Eq. (1), where l_i is the ith ship and n is the number of ships in 15 min,

$$totalSPL_w = 10log_{10}\sum_{i=1}^{n} 10^{l_i/10}. \quad (1)$$

The ship locations were determined for the mid-point of each 15 min time period. The ships were assumed to remain

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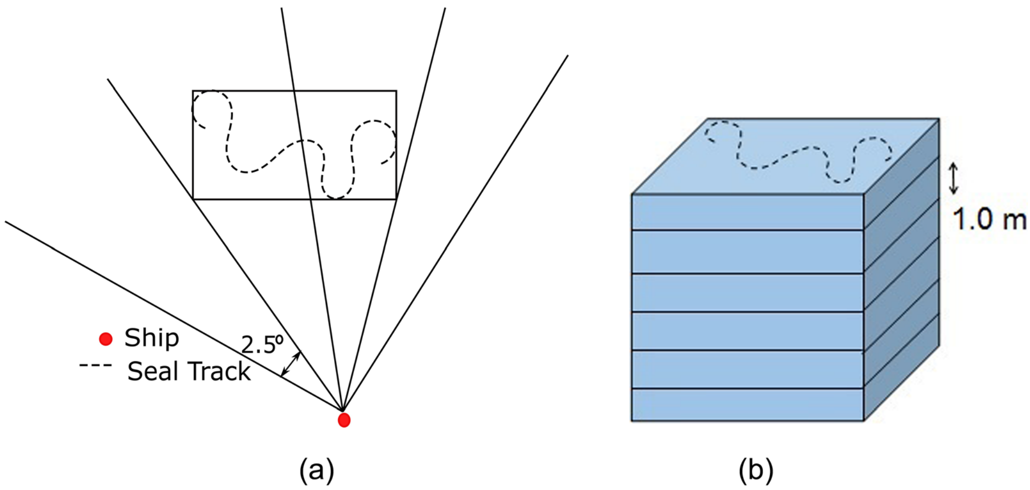

FIG. 3. (Color online) Diagram of methodology used to create the received noise field for each 15 min of seal track. For each 15 min track segment, the track was enclosed in a rectangle. For each ship, the bearing between the ship and corners of the rectangle were calculated. The maximum bearing was increased and the minimum bearing was decreased by 2.5° to ensure complete coverage of the seal track and transects between the two outer transects were created at an azimuth of 2.5°. Propagation loss and hence received SPLs were calculated along each transect and at every 1 m in depth. (a) Top view; (b) depth view.

stationary during each 15 min period and the seal moved throughout the noise field. It is recognised that in reality, the ships and seals would move relative to each other in a 15 min period. However, the computational time required to recalculate the sound field using the RAMSurf model is a key factor in determining the possible temporal resolution for noise calculations. This parameter was included in a sensitivity analysis (see Supplemental Material[1]) that demonstrated the sufficient accuracy of a 15 min resolution.

All ships within 120 km of the seals' location in a 15 min period were included in noise calculation estimates. It was a precautionary threshold to include all possible ships contributing to noise levels. Seals located close to the boundary would be exposed to fewer ships due to the lack of AIS data outside the boundary. To combat this issue, a 15 km buffer zone was implemented. Seal tracks only touched the edge of the 15 km buffer zone on 5 of 86 days.

F. 24-h sound exposure levels and prediction of auditory damage

The exposure of the seal to shipping noise was linearly interpolated from the sound field for each 24-h period to give sound exposure levels with a temporal resolution of 1 s (i.e., a noise exposure value was predicted at the seal's location every 1 s). The temporal exposure period of 24 h is arbitrary (National Marine Fisheries Service, 2018; Southall *et al.*, 2019). However, this is the standard cumulative period utilised by National Marine Fisheries Service (2018) for assessing auditory threshold shift.

Sound exposure has the potential to have a negative impact on auditory systems through permanent threshold shift or temporary threshold shift, as well as instigate maladaptive behavioural or physiological responses (Hastie *et al.*, 2018; Rolland *et al.*, 2012; Southall *et al.*, 2019). Consequently, this study reports two sound exposure values, 24-h SEL_w and 24-h SEL_w above effective quiet. The 24-h SEL_w represents the total contribution of shipping noise perceivable by seals to the soundscape (ISO, 2017) (given the limitations in AIS data) and includes weighted SPLs emitted by ships that, while may not be at an intensity to cause auditory damage, may be pertinent in assessing behavioural responses to noise levels or when assessing the contribution of shipping to the wider soundscape. The 24-h SEL_w above effective quiet was calculated by removing SPL_w values below an estimated level of effective quiet for grey seals, 124 dB re 1 μPa^2 (Finneran, 2015). Effective quiet can be defined as the exposure levels which neither result in TTS nor retard the recovery of TTS from a previous exposure (Ward *et al.*, 1976). It recognises that some sound exposures are at a level that no matter how long the exposure lasts, it will never result in TTS (Ward *et al.*, 1976). It is important to consider the effective quiet threshold when calculating sound exposure levels because accumulating low sound levels over long durations may result in an inflated impression of sound levels (Finneran and Branstetter, 2013). However, there is very little data on appropriate levels of effective quiet in marine mammals (Finneran, 2015). Hence, the value used here was estimated by Finneran (2015) when considering the lowest value known to cause TTS in pinnipeds. The two types of sound exposure levels were weighted using the Southall *et al.* (2007) frequency weighting function and compared to the best estimate value of 183 dB re 1 $\mu Pa^2 s$ for the onset of TTS in pinnipeds with respect to non-impulsive sounds (Southall *et al.*, 2007). For comparison, they were also weighted using the updated frequency weighting function proposed by Southall *et al.* (2019) and compared to the corresponding threshold of 181 dB re 1 $\mu Pa^2 s$ for the onset of TTS in phocid pinnipeds (Southall *et al.*, 2019). Uncertainty estimates associated with modelled values are provided in the Supplemental Material.[1]

G. Analysis of shipping traffic

The relative influence of ship source levels, distance, and the number of ships on the calculated sound exposure levels from shipping was analysed using a Generalised Additive Mixed Model (GAMM). GAMMs allows for non-linear relationships between the response variable and the explanatory variables and the inclusion of random effects. The response variable, 15-min SEL_w (i.e., SEL_w integrated over 15 min and weighted using frequency weighting function proposed by Southall *et al.*, 2007), was modelled using the explanatory variables, closest point of approach of a ship (CPA), defined as the minimum separation distance between a seal and any of the ships in the 15 min section, the maximum source level of any ship in the 15 min (SL_{max}), the number of ships within 120 km of the seal for those 15 min (NUM), and the location of the seal (English Channel or Celtic Sea). CPA, NUM, and SL_{max} were included in the model as individual smooths as well as a multivariate smoothed term using tensor product smooths of cubic regression splines (Wood, 2006). This was appropriate because each covariate was not isotropic (i.e., they did not have the same scale) (Wood, 2006). The GAMM models were implemented in R version 3.5.3 (R Core Team, 2019) using the mgcv package version 1.8–28 (Wood, 2003, 2004, 2006). The models were implemented using a Gaussian error structure with an identity link function. The response variable was log transformed [$log(y)$] to improve the normality of the residuals where different model families (e.g., Gamma) did not improve the model.

The random variable seal was included to account for the possibility of greater similarity between the exposures of an individual seal compared to other seals. Each 15 min sample was highly autocorrelated because it was likely to contain the same ships as those before and after it. As a result, the data were subsampled and every tenth 15 min section was included in the model. The inclusion of a spherical correlation structure [$corSpher(form = \sim 1|seal)$] reduced any remaining autocorrelation between the residuals where necessary. Model selection was completed using Akaike's Information Criterion (AIC) and followed the methodology laid out by Zuur (2009) by first creating a model with all variables, determining the random structure that gave the lowest AIC and then determining the optimum fixed effects structure by removing variables and comparing AIC values. AIC was given by $-2loglikelihood + 2k$, where k is the number of parameters. Model validation was completed by visual inspection of the residuals.

III. RESULTS

A. Shipping traffic and seals

The weighted sound exposure levels of adult grey seals in the English Channel and grey seal pups in the Celtic Sea varied as they moved throughout their environment, particularly, lower received levels resulted from scattering and absorption at the boundaries with the surface and bottom of the ocean (Figs. 4 and 5). Spatial variation in received noise levels was driven in part by the number of ships, the source level of the ships and the distance between the seal and the ship. In a 15 min period, within 5 km of the seal, the mean number of ships was only 1.1 (SD = 0.3) for the Celtic Sea and 1.3 (SD = 0.5) for the English Channel. However, within 120 km of the seal, this was higher for the English Channel group at 26.9 (SD = 24.5) ships and lower for the Celtic sea group at 6.5 (SD = 7.2) ships, highlighting the overall busier nature of the greater English Channel area (Fig. 2).

The CPA between a seal and any of the ships in a 15 min section, was 161 m for the English Channel seals and 535 m for the Celtic Sea seals. The majority of 15 min sections (52%) had a CPA below 35 km. For the English Channel seals 65% of CPA for ships were below 35 km, whereas ships in the Celtic Sea were generally not as close to the seals and only 41% of CPA were below 35 km.

The source levels of ships included in the predictions were greater in the English Channel (median = 176 dB re 1 μPa^2m^2, Inter-Quartile Range, IQR = 46 dB) than the Celtic Sea (median = 170 dB re 1 μPa^2m^2, IQR = 34 dB). This difference was even more stark when only considering those ships that were within 5 km of the seal. The median source level in the English Channel was 177 dB re 1 μPa^2m^2 (IQR = 30 dB) but this was only 154 dB re 1 μPa^2m^2 (IQR = 20 dB) in the Celtic Sea. Seals included in the study in the Celtic Sea, generally utilised areas located further from the major shipping lanes where the largest ships are concentrated (Figs. 1 and 2).

The relationship between 15-min SEL_w, the CPA of a ship, maximum ship source level (SL_{max}), and the number of ships within 120 km of the seal (NUM) in that 15 min was modelled using a GAMM. The model, following stepwise model selection using AIC, included the multivariate smooth of CPA, NUM, and SL_{max}, as well as the main effect smooths of SL_{max} and CPA as significant explanatory variables (Table II). It did not include location or the number of ships as an individual smooth (Table II). The 15-min SEL_w decreased as the CPA increased, and 15-min SEL_w increased as the maximum ship source level increased. As the CPA increased, noise remained constant if the maximum source level increased and/or the number of ships increased. This relationship did not differ between the Celtic Sea or English Channel. However, in the Celtic Sea, there are fewer 15 min sections with high numbers of ships, a close approach and high SL_{max} than the English Channel (Fig. 6). Model validation plots are included in the Supplemental Material[1] and show the residuals and autocorrelation were appropriately modelled.

The relationship between CPA, NUM, and SL_{max} can be examined more closely in Figs. 4 and 5, which also show the distance between a seal and the ships that were included in the soundscape calculations. Figure 4 shows three peaks in SPL_w greater than 105 dB re 1 μPa^2 just before 12:06, at 14:53, and between 23:13 and 02:00. The high noise levels at the seal are mediated by the source level of the ship, how

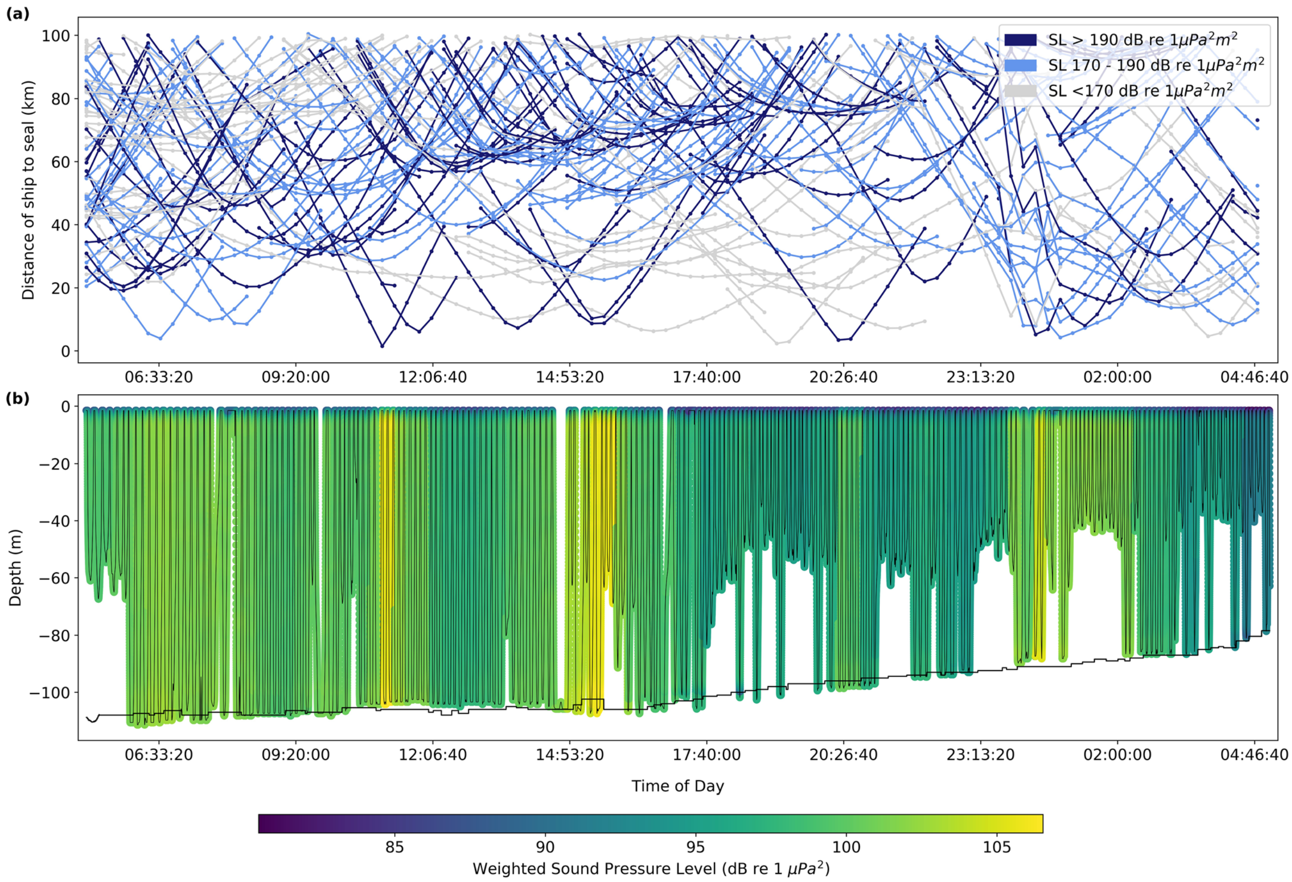

FIG. 4. (Color online) Distance between the seal and each ship (a) and the weighted received SPLs along the dive track of Seal B23 for 24 h in the English Channel (b). The source level of each ship is classified to show the loudest ships. The noise levels are a reflection of the number of ships, distance between seal and ships, and the source level of each ship. The total number of ships in each source level category was 87, 116, and 93 for >190, 170–190, and <170 dB re 1 μPa^{2}m^2, respectively. Time of day starts at 29th October 2011 05:05:00. Black horizontal line indicates bathymetry. Black vertical lines indicate seal dives. Values were weighted as proposed by Southall *et al.* (2019). Dives below the bathymetry arise from bathymetry referenced to mean seal level, the seal diving throughout the tidal cycle, and location error.

close the ship came to the seal, and the number of ships. Just before 12:06 at Peak 1 a loud ship (>190 dB re 1 μPa^{2}m^2) is close to the seal. At Peak 2 just after 14:53, the ships are further away from the seal than during Peak 1 but there is a second loud ship and the presence of a quieter ship (<170 dB re1 μPa^{2}m^2) in the area, which results in similar overall noise levels at Peak 1 and 2. The peak in noise between 23:13 and 02:00 has a high number of different ships, which results in sustained noise levels across the time despite variation in traffic. At 20:26, a loud ship results in higher noise levels; just before this, a ship follows an almost identical path to the ship at 20:26, but the lower source level of the ship results in lower noise levels.

B. 24-h sound exposure levels

The 24-h SEL_w ranged from 124 to 170 dB re 1 μPa^{2}s for all seals for a total of 86 days (Fig. 7) when weighted using the underwater pinniped frequency weighting function proposed by Southall *et al.* (2007). Median 24-h SEL_w for all seals was 149 dB re 1 μPa^{2}s. Median 24-h SEL_w for the Celtic Sea pups was 143 (129–156) dB re 1 μPa^{2}s and 159 (124–170) dB re 1 μPa^{2}s for the English Channel adults. These values represent the total exposure of seals to shipping noise during these 24 h periods. However, SPL_w values throughout the 24 h ranged from 0 to 140 dB re 1 μPa^2 with the median value of the maximum SPL_w on each of the 86 days being 115 dB re 1 μPa^2. In contrast, 24-h SEL_w was between 9 and 18 dB lower when weighted using the updated underwater frequency weighting function for phocid pinnipeds proposed by Southall *et al.* (2019). Median 24-h SEL_w for the Celtic Sea pups was 128 (118–140) dB re 1 μPa^{2}s and 142 (106–152) dB re 1 μPa^{2}s for the English Channel adults with a maximum SPL_w of 121 dB re 1 μPa^2 and median maximum SPL_w of 99 dB re 1 μPa^2 for all seals.

In order to assess if TTS could occur in the seals, 24-h SEL_w above effective quiet was also calculated using only exposures to SPL_w greater than or equal to the value of effective quiet (124 dB re 1 μPa^2) in a 24 h period. For the values weighted as proposed by Southall *et al.* (2007), the number of days with 24-h SEL_w above zero decreased dramatically from 86 to 18 when considering only SPL_w greater than or equal to the value of effective quiet. Mean exposure duration above effective quiet was 38.57 (SD = 47.86) minutes (Table III). All but one of the days with SPL_w above effective quiet were for seals in the English Channel. 24-h

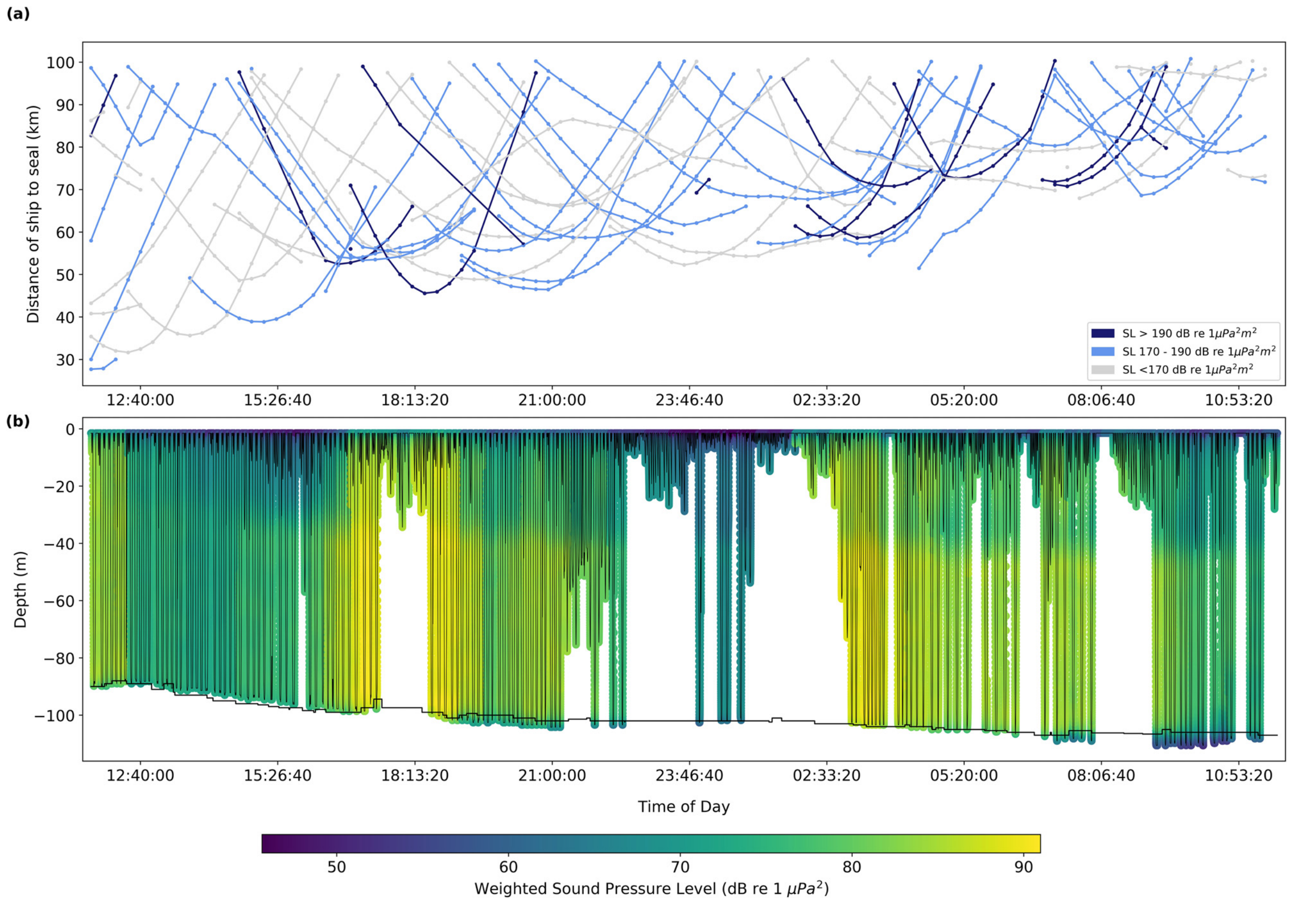

FIG. 5. (Color online) Distance between the seal and each ship (a) and the weighted received SPLs along the dive track of Seal hg29-11-10 in 24 h in the Celtic Sea (b). The source level of each ship is classified to show the loudest ships. The noise levels are a reflection of the number of ships, distance between seal and ships, and the source level of each ship. The total number of ships in each source level category was 13, 36, and 35 for >190, 170–190, <170 dB re 1 μPa^{2}m^2, respectively. Time of day starts at 21st June 2011 at 11:40:00. Black horizontal line indicates bathymetry. Black vertical lines indicate seal dives. Values were weighted as proposed by Southall *et al.* (2019). Dives below the bathymetry arise from bathymetry referenced to mean seal level, the seal diving throughout the tidal cycle, and location error.

SEL_w above effective quiet ranged from 141 to 169 dB re 1 μPa^{2}s with a median value of 154 dB re 1 μPa^{2}s although, for the majority of days, 68 of 86, the 24-h SEL_w above effective quiet was zero (Table III). Similarly, when values were weighted using the updated function by Southall *et al.* (2019), there were no instances where SPL_w was greater than or equal to the value of effective quiet (124 dB re 1 μPa^2) in any 24 h period. The estimated values did not exceed the threshold of 183 or 181 dB re 1 μPa^{2}s for the onset of TTS when weighted using functions by Southall *et al.* (2007) and Southall *et al.* (2019), respectively. The inter-quartile range of predicted 24-h SEL_w values given estimated uncertainty in model predictions was between 2 and 6 dB for all seals (see Supplemental Material[1]).

IV. DISCUSSION

This study presented predictions of the 24-h weighted sound exposure levels for grey seals given the three-dimensional at-sea behaviour of individual seals. For pups

TABLE II. The structure of the maximal model with all explanatory variables and each model tested during model selection for the response variable 15 minute weighted sound exposure level.

Model	*df*	R^2 (adj)	AIC	△ AIC
A: Full[a]	15	0.66	−1242	
B: Full - Location[b]	14	0.64	−1248	−6
C: B—NUM[c]	12	0.63	−1250	−2
D: C—CPA[d]	10	0.61	−1188	62

[a] $log(15SEL_w) \sim ti(SL) + ti(num) + ti(CPA) + ti(CPA, NUM, SL) + location + (1|seal) + corSpher(1|seal))$.
[b] $log(15SEL_w) \sim ti(SL) + ti(num) + ti(CPA) + ti(CPA, NUM, SL) + (1|seal) + corSpher(1|seal))$.
[c] $log(15SEL_w) \sim ti(SL) + ti(CPA) + ti(CPA, NUM, SL) + (1|seal) + corSpher(1|seal))$.
[d] $log(15SEL_w) \sim ti(SL) + ti(CPA, NUM, SL) + (1|seal) + corSpher(1|seal))$.

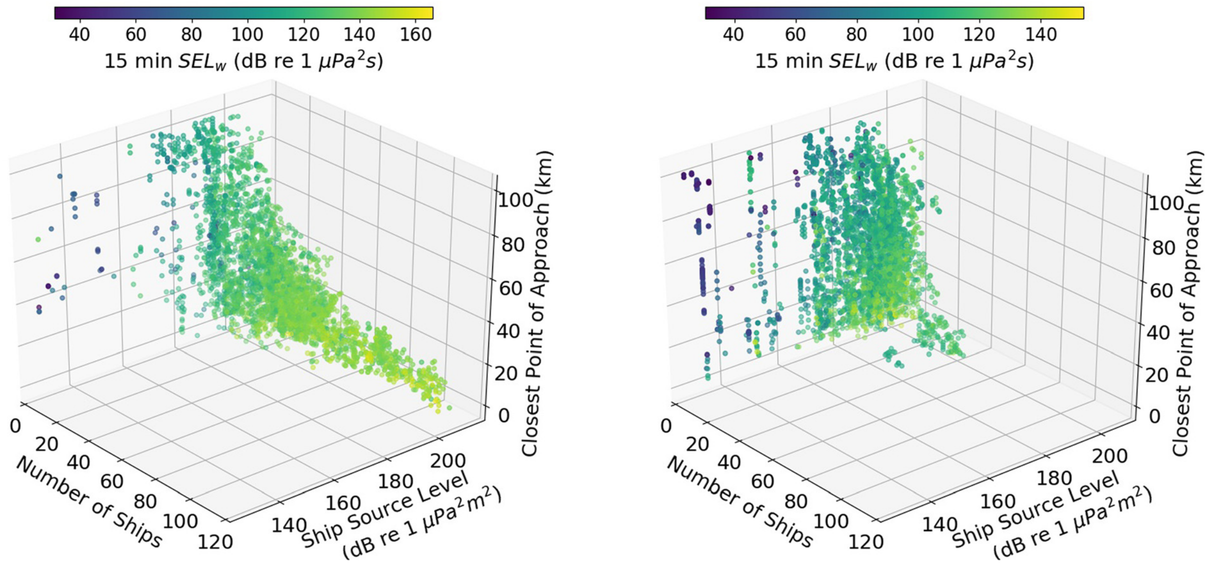

FIG. 6. (Color online) The weighted sound exposure level SEL_w in 15 min given the number of ships, the CPA for a single ship, and the maximum ship source level in that 15 min period in the English Channel (left) and the Celtic Sea (right). Note different scales. The 15-min SEL_w were weighted using frequency weighting function for underwater pinnipeds proposed by Southall *et al.* (2007). The Celtic Sea has fewer of the high noise scenario data points with high source levels, a close approach, and high ship numbers.

primarily located in the Celtic Sea, median 24-h SEL_w was 143 dB re 1 μPa^{2}s, and for adults primarily located in the English Channel, median 24-h SEL_w was 159 dB re 1 μPa^{2}s (using the Southall *et al.*, 2007 frequency weighting function). It is not possible to give direct comparisons between the two areas or between the adults and pups because data were only available for pups in the Celtic Sea region and adults in the English Channel region confounding any possible comparative analysis. However, given the results presented here, it is reasonable to assume that differences in shipping activity are a driver of differential noise exposure in the two groups. Merchant *et al.* (2016) highlighted that 125 Hz octave band noise in the south-eastern Celtic Sea was quieter than Falmouth Bay in the English Channel, and noted it as one of the quietest regions compared to locations in the North Sea. The mean 24-h SEL_w recorded using a hydrophone in Falmouth Bay and weighted using the Southall *et al.* (2007) m-weighting curve for pinnipeds was 156 ± 19.1 dB re 1 μPa^{2}s, a remarkably similar match to average exposure for seals in the English Channel (Merchant *et al.*, 2012). The seals occupy water south-west of Falmouth Bay in busier and, therefore, noisier waters, but their occupation of these waters is temporary because they are transiting through the area unlike the stationary hydrophone in Falmouth Bay. The results are also between 20 and 36 dB lower than 24-h SEL_w values reported for harbour seals in the Moray Firth (Jones *et al.*, 2017). This disparity could arise from differences in shipping traffic but also the propagation model used, the two-dimensional modelling approach, and the wider frequency range (12.5 Hz–20 kHz) studied by Jones *et al.* (2017). In addition, Jones *et al.* (2017) studied harbour seals which do not travel as far from haul-out sites (Thompson *et al.*, 1996), and, therefore, may be more resident in areas of high shipping traffic. However, the results highlight spatial variation in noise patterns and shipping traffic in different regions. It provides evidence that regional variations must be considered carefully in underwater noise management plans.

SPL_w values ranged from 0 to 140 dB re 1 μPa^2 and median maximum SPL_w in a day was 115 and 99 dB re 1 μPa^2 when weighted as proposed by Southall *et al.* (2007) and Southall *et al.* (2019), respectively. Ambient sound levels (ISO, 2017) absent of shipping noise in the region were not available as part of this study, but measurements by Merchant *et al.* (2016) at one location in the Celtic Sea suggested median ambient sound levels to be 83.3 dB re 1 μPa^2 at 125 Hz. In the English Channel, recordings from Falmouth Harbour measured broadband (0.01–1 kHz) SPLs between 86.1 and 148.6 dB re 1 μPa^2 and the minimum recorded level (representative of ambient sound in the absence of shipping) was 96.2 dB re 1 μPa^2 (Merchant *et al.*, 2012). These values suggest that the seals were exposed to sound from shipping above that which could be considered ambient sound levels in both the Celtic Sea and English Channel. However, the estimated level of effective quiet for grey seals is 124 dB re 1 μPa^2 and the SPL_w values remained below this for many of the seals.

The SEL_w in 15 min was closely related to the number of ships, the CPA of any ship, and the source level of the loudest ships in that 15 min. For example, ships with high source levels over 50 km from the seal still resulted in received SPL_w greater than 100 dB re 1 μPa^2 for a seal in the Celtic Sea (Fig. 5). These exposures may be indistinguishable from ambient sound for seals, but they will raise the overall ambient sound levels and may be of concern for issues such as call masking and chronic stress related to sustained exposure (Rolland *et al.*, 2012). Ship noise exposure detectable above ambient sound levels will be most relevant

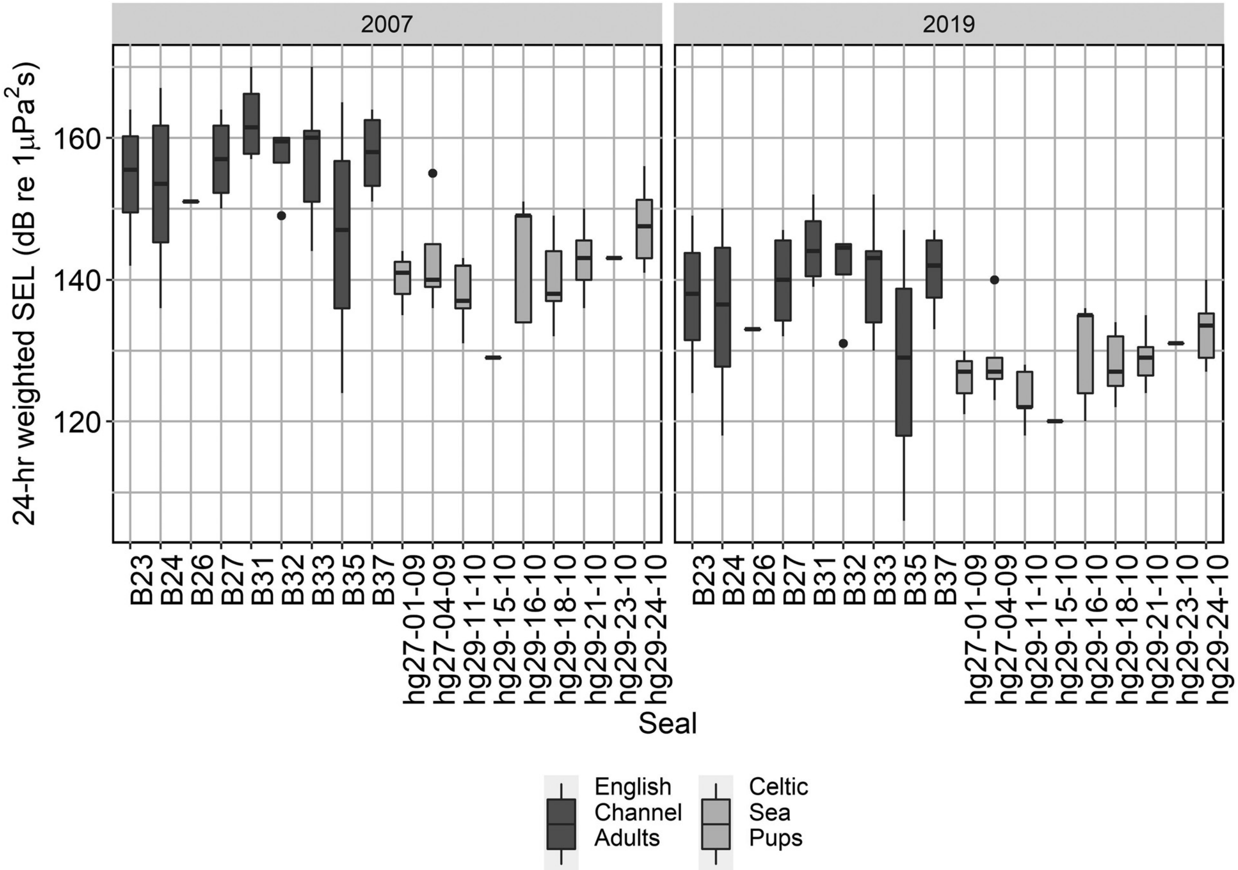

FIG. 7. The 24-h weighted sound exposure levels for adult seals in the English Channel and pups in the Celtic Sea. The values were weighted using the frequency weighting function for underwater pinnipeds from Southall *et al.* (2007) (left panel) or underwater phocid pinnipeds from Southall *et al.* (2019) (right panel). A total of 86 days were processed for nine adult seals and nine seal pups.

TABLE III. The 24-hr weighted sound exposure levels (SEL_w) including only SPL_w greater than effective quiet set at a value of 124 dB re 1 μPa^2. The number of minutes SPL_w was greater than effective quiet and the maximum SPL_w predicted in 24-h. Values were weighted as proposed by Southall *et al.* (2007). When weighted using function for phocid pinnipeds proposed by Southall *et al.* (2019), there were no SPL_w above effective quiet.

Seal	Maximum SPLw (dB re 1 μPa^2)	24-hr SELw above effective quiet (dB re 1 μPa^{2}s)	Minutes above effective quiet
B31	133	162	34
B31	134	168	176
B32	126	152	9
B32	124	142	1
B35	130	159	24
B37	126	158	38
B32	126	153	10
B27	131	162	52
B23	126	154	12
B24	130	164	107
B24	125	141	0.8
B31	126	153	12
B33	140	169	90
B33	128	156	13
B33	125	147	3
B33	138	168	90
B37	126	153	12
hg29-24-10	126	154	10

for determining auditory damage and possible behavioural responses to noise, and these generally arose from ships closer to the seal and with higher source levels. However, the results demonstrated the ability of high numbers of loud ships far away from the seal to generate high noise exposure levels at the seal's location. This suggests that when assessing the impacts of shipping noise, the area over which ships are included in calculations of noise levels should be sufficiently wide to capture such exposure and not just focus on the first few kilometres from the seal (Mikkelsen *et al.*, 2019).

In addition to shipping traffic alone, the difference in behaviour between English Channel adults and Celtic Sea pups as a result of age or location specific factors such as bathymetry may also be mediating noise exposure in the two groups. Figure 1 shows that the seals in the Celtic Sea were mainly located to the north of the region where shipping density is lower. English Channel seals cross an area of very high intensity shipping. However, compared to their whole track they tend to make this crossing only once or twice, and visual inspection of the track suggests they are undertaking directed travel through the area. The majority of their time was spent around the islands within the Iroise Marine Park. The noise levels in this area are unknown but are likely to be different as a result of lower numbers of large ships. Huon *et al.* (2015) studied 19 seals, nine of

https://doi.org/10.1121/10.0001727

which are included here, and found that individuals spent 67% of their time within the Marine Park. Harbour seals in the Moray Firth, which experience much higher cumulative noise levels, also tend to remain close to the coast. However, they are resident within the zones of higher intensity shipping (Jones *et al.*, 2017). This could account for their higher exposure.

Recommendations for appropriate frequency weighting functions and TTS onset thresholds have been systematically updated with the availability of new audiometric studies and approaches (National Marine Fisheries Service, 2018; Southall *et al.*, 2007; Southall *et al.*, 2019). Specifically, Southall *et al.* (2019) present separate frequency weighting functions and TTS onset thresholds for otariid and phocid pinnipeds. When compared to the underwater pinniped frequency weighting function proposed by Southall *et al.* (2007), this updated function for phocid pinnipeds underwater shows reduced hearing sensitivity at low frequencies. This is particularly true between 10 and 1000 Hz, the dominant frequencies emitted by ships. This accounts for the 9–18 dB difference between 24-h SEL_w using the two functions. However, Southall *et al.* (2019) recognise limits on high frequency hearing exceeded 60 kHz for many phocid species. Therefore, it may be necessary to consider a wider frequency range when predicting the exposure of phocid pinnipeds to shipping noise. Southall *et al.* (2007) took a necessarily cautious approach due to the limited available data. This approach may still be useful if a regulatory scenario also requires a precautionary approach, and when comparing predicted exposure to historical measurements that have been subsequently frequency weighted.

Southall *et al.* (2019) proposed that, given the best available data, phocid seals will experience TTS for underwater non-impulsive sounds such as shipping noise when weighted sound exposure levels exceed 181 dB re 1 $\mu Pa^2 s$. In older recommendations, this threshold was 183 dB re 1 $\mu Pa^2 s$ (Southall *et al.*, 2007). The exposure of seals above effective quiet in this study did not exceed these threshold values when weighted using the appropriate comparable frequency weighting function. For the most precautionary approach, using Southall *et al.* (2007) frequency weighting functions, eight adults and one pup for a total of 18 days experienced SPL_w greater than the values of effective quiet. The 24-h SEL_w above effective quiet range from 141 to 169 dB re 1 $\mu Pa^2 s$ and as such are between 14 and 42 dB below the threshold level for TTS. Auditory weighting functions and TTS onset thresholds have been derived from direct measurements of hearing thresholds, consideration of auditory anatomy, and data on sound production capabilities (Southall *et al.*, 2019). However, these studies often utilise only one or two individuals (Southall *et al.*, 2019). Furthermore, there is very limited auditory data specifically studying the underwater hearing of adult grey seals or pups (Finneran, 2015; Southall *et al.*, 2019). Pups may be more sensitive to noise but future work is necessary to explore the sensitivity of animals in this vulnerable juvenile stage.

Temporary threshold shift is determined by exposure frequency, duration, SPL, temporal pattern of noise, and available recovery time (Finneran and Branstetter, 2013; Finneran, 2015). Kastak and Schusterman (1999) found average threshold shift of 4.8 dB given exposure for 20 min at 100 Hz to SPLs ranging from 133 to 156 dB re 1 μPa^2. These conditions were met three times in this study. Many studies of TTS growth and recovery in phocid seals examined frequencies higher (2.5–4 kHz) than the peak shipping noise used in this study (10–1000 Hz) and higher SPL values than seals were exposed to in these calculations. Kastelein *et al.* (2012) tested the hearing of two harbour seals using octave band noise at a centre frequency of 4 kHz. They showed maximum TTS of 10 dB 1–4 min after a 120 min exposure to 148 dB re 1 μPa^2. TTS began to occur at SPLs of 136 dB for 60 min. This suggests any one of the properties (exposure frequency, duration, etc.) determining TTS should be closely monitored for changes that may result in exposures great enough to induce TTS. In addition, mitigation measures to address any detected increase in underwater noise from shipping should consider the impact of SPLs but also exposure duration and frequency, given their ability to influence levels of TTS experienced by the seals (Finneran and Branstetter, 2013; Finneran, 2015; Joy *et al.*, 2019).

Twenty-four hour sound exposure levels are often considered for regulatory assessments because the metric considers the duration of exposure as well as SPL and frequency (Finneran and Branstetter, 2013). The standard duration of exposure for non-impulsive sounds such as shipping noise has been 24 h (National Marine Fisheries Service, 2018; Southall *et al.*, 2007). However, it is recognised that this is an arbitrary value (Southall *et al.*, 2019). If a species shows high site fidelity at a high exposure zone they may be exposed for much longer than 24 h. Alternatively, individuals may move in and out of high exposure zones. Particularly, for sources such as ships that are highly mobile, peaks in noise may be quite short and an individual may have periods where shipping noise could be zero. The development of a more ecologically relevant value is key for future policy and management of noise (National Marine Fisheries Service, 2018). Seals spend time at-sea between periods of haul-out; therefore, the duration over which seals are potentially exposed to underwater noise varies and supports the assertion that the accumulation period appropriate for a specific species or noise source will vary. The mean length of exposures above effective quiet in 24 h was 38.47 min but some of the Celtic Sea pups spent greater than 2 months at sea (Carter *et al.*, 2017). The 24-h SEL_w metric assumes the "equal energy" hypothesis, whereby exposures of equal energy are assumed to result in the same amounts of threshold shift regardless of how the exposure is distributed in time (Finneran and Branstetter, 2013). It is known that the equal-energy approach overestimates intermittent exposures because it does not consider the recovery that can occur from TTS between the noise exposures within the total accumulation period (Finneran and Branstetter, 2013). Hence, for seals, a continuous accumulation period of 24 h, as used in this study, may result in higher levels of TTS than if periods of haul-out and recovery are included.

In addition to possible auditory damage, behavioural responses and physiological responses have been recorded for a number of marine species to shipping noise (Blair *et al.*, 2016; Celi *et al.*, 2015; Rolland *et al.*, 2012; Williams *et al.*, 2002). Seals have shown behavioural reactions such as entering the water, decrease in resting behaviour, and increase in alert behaviour at the sight of approaching boats and boat noise playbacks when hauled out (Jansen *et al.*, 2015; Tripovich *et al.*, 2012). There is only limited anecdotal evidence of changes in the at-sea behaviour of seals in response to shipping noise (Mikkelsen *et al.*, 2019). As such, acceptable exposure levels with respect to behavioural changes are unknown, and crucially, if there is a behavioural response, what level of behavioural response is harmful for individual survival and population stability (McHuron *et al.*, 2017). The results show that seals are exposed to shipping noise and this is likely to be above ambient sound levels generated by other sound sources. Therefore, further assessment of the behavioural responses of seals to this noise is warranted. This may be especially true of grey seal pups that are potentially naive to underwater anthropogenic noise when they leave breeding colonies for the first time. To avoid starvation, they must rapidly develop at-sea movement and foraging behaviour without parental guidance, making them vulnerable to disturbance (Carter *et al.*, 2017). Furthermore, the prolonged immaturity of grey seal pups (5-year-old females; 10-year-old males) means that increased pup mortality will not immediately manifest itself in observable population dynamics (Harwood and Prime, 1978).

Exposure levels and at-sea spatial usage are key parameters in understanding the spatial risk for marine animals of exposure to shipping noise and are required to set effective management targets (Erbe *et al.*, 2014). The results can contribute to the estimation of noise budgets and assessments of soundscapes that will help close the gap to establishing quantitative noise level targets that regulators can enforce. As described by Merchant *et al.* (2017), population density and noise exposure can be combined to provide risk maps. This is a similar approach as that implemented by Erbe *et al.* (2012a). However, the majority of the distribution and noise based information is related to two-dimensional maps. In contrast, the results presented assess the noise exposure for seals using their three-dimensional dive track and adds the new dimension of depth to risk based assessment of noise levels for management goals. The results suggest that when seals are located at the surface or at the sea floor, they may experience lower noise levels due to surface and bottom losses. This observation highlights the potential importance of considering three-dimensional space use by marine animals when calculating exposure, especially those that utilise the complete water column (Chen *et al.*, 2017).

The predictions presented in this study are subject to a number of limitations and uncertainties, including the source level estimates (Simard *et al.*, 2016), missing ships and incomplete transects in the AIS data (Hermannsen *et al.*, 2019), and uncertainty in the environmental input data. The inter-quartile range of predicted 24-h SEL_w values given estimated uncertainty in model predictions was between 2 and 6 dB for all seals (see Supplemental Material[1]). The resulting noise exposure estimates should be viewed in this context and in combination with noise estimates for other noise sources. However, this study used a sophisticated acoustic propagation model that has been benchmarked and compared to experimental data (Davis *et al.*, 1982; Hanna and Rost, 1981). RAMSurf considers detailed representations of environmental properties that are particularly important in shallow water propagation scenarios. It has been highlighted that in such scenarios, simple spreading laws can result in significant errors (Farcas *et al.*, 2016; Robinson *et al.*, 2014). The uncertainties associated with the simple spreading model could account for some of the differences seen in ship noise exposure between the Moray Firth and the region of south-west UK considered here. Validation of the Jones *et al.* (2017) model alone suggests that median absolute error in the model was 9.75 (2.11–24.51) dB (Jones *et al.*, 2019).

In summary, at-sea, three-dimensional exposure of grey seals to shipping noise ranged from 124 to 170 dB re 1 $\mu Pa^2 s$ in 24-h when weighted using the underwater frequency weighting function for pinnipeds proposed by Southall *et al.* (2007). However, only nine seals were exposed to weighted SPLs greater than the estimated value of effective quiet for phocid seals, and 24-h SEL_w based on exposures above effective quiet ranged from 141 to 169 dB re 1 $\mu Pa^2 s$. In contrast, when values are weighted using the updated frequency weighting function for underwater phocid pinnipeds, 24-h SEL_w was between 106 and 152 dB re 1 $\mu Pa^2 s$ and SPL_w did not exceed effective quiet on any occasion. The exposure of seals to shipping noise did not exceed best evidence thresholds for TTS. The exposure of the seals was mediated by the number of ships, CPA of these ships, maximum ship source level, and the at-sea behaviour of the seals. This study presents vital data on the exposure of grey seals and the influence of shipping traffic on this exposure. This is central to our understanding of the risks posed by shipping noise and can inform marine spatial planning in the future. A major obstacle to concrete policy commitments on shipping noise is a lack of understanding of marine noise budgets, which characterise the contribution of different noise sources to the overall underwater soundscape (Merchant *et al.*, 2017). Exposure values reported here contribute to such noise budgets by representing the total contribution of shipping to the seals' soundscape.

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[1]See supplemental materials at https://doi.org/10.1121/10.0001727 for details of the acoustic model parameters, sensitivity analysis, estimation of uncertainty, and model validation plots.

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